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Effects of climate change and human activities on runoff in the Beichuan River Basin in the northeastern Tibetan Plateau, China

Xianbang Wang, Kangning He*, Zhe Dong

College of Soil and Water Conservation, Beijing Forestry University, Key Laboratory of State Forestry Administration on Soil and Water Conservation, Beijing 100083, China

Beijing Forestry University, Beijing Engineering Research Center of Soil and Water Conservation, Beijing 100083, China

Beijing Forestry University, Engineering Research Center of Forestry Ecological Engineering, Ministry of Education, Beijing 100083, China

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ABSTRACT

Climate change and human activities are considered to be the main drivers of runoff changes. Assessing their contributions is important for maintaining the integrity of the water cycle process and promoting the healthy management of water resources. But the contributions of these two factors in the Beichuan River Basin remain unclear. In this study, hydrological and meteorological data from six sub-basins (Niuchang, Xiamen, Heilin, Qiaotou, Dongxia, and Chaoyang) during 1961–2013 were studied to elucidate upon the effects of these processes. Mann-Kendall tests showed that runoff in the Beichuan River Basin showed a downward trend over the study period and revealed that abrupt changes occurred in 1972 and 1989. Therefore, the study period was divided into two periods: a base period and a change period (periods I and II). A climate elasticity model and hydrological sensitivity analysis were used to estimate the contributions of climate change and human activities. We found that the dominant factors in changing runoff were human activities. Due with the conversion of cropland to forest and grassland and increases of construction land, during the change period water supply increases evidently. Among the basin regions, the Chaoyang sub-basin showed the greatest runoff decline and an abrupt change in 1989, and human activities had the greatest contribution to runoff change in this sub-basin. In addition, the conversion of cropland to forest and grassland was most evident in the Chaoyang and Qiaotou sub-basins, and the area of construction land in these two regions increased greatly during the change period.

1. Introduction

In recent decades, the demand for water resources in terms of both quality and quantity has become an increasingly serious problem at the watershed scale (Lakshmi et al., 2011; Tomer and Schilling, 2009). The key to identifying the influential factors of runoff is to establish a set of water resource management plans as soon as possible (Wei and Zhang, 2010). Climate change and changes in human activities have significant impacts on hydrological cycle processes (Jiang et al., 2015; Piao et al., 2010; Zhao et al., 2014). In a catchment area, the hydrological cycle is a very complex process (Wang and Tang, 2014; Wang et al., 2014). Climate change and human activities are widely believed to be two main drivers of runoff change (Huntington, 2006; Lin et al., 2007; Piao et al., 2007; Zhang et al., 2014b). Climate change leads to elevate temperatures and changes in precipitation and evapotranspiration, which strongly impact regional hydrological processes (Zheng et al., 2009). The effects of human activities can be divided into direct and indirect effects; direct effects include irrigation, industrial and agricultural water uses which directly obtained water from rivers. Indirect effects include afforestation and urban construction have changed the patterns of land use and consequently the hydrological cycle, thus affecting the spatial and temporal distribution of water resources (Li et al., 2007; Ma et al., 2008; Scanlon et al., 2007; Yang and Fei, 2009b; Zhang et al., 1944).

In recent years, scholars have conducted extensive research on the relationships between climate change and human activities, and substantial efforts have been made to understand the influences and relative importances of climate variation and human activities on the hydrological cycle and water resources (Ahn and Merwade, 2014; Jiang et al., 2011; Kong et al., 2016; Tang et al., 2014). Sun et al. (2013) used climate elasticity in the Poyang Lake Basin to analyze the effects of climate change on annual streamflow. Runoff in the Yangtze and

* Corresponding author at: College of Soil and Water Conservation, Beijing Forestry University, Key Laboratory of State Forestry Administration on Soil and Water Conservation, Beijing 100083, China.

E-mail address: hkn@bjfu.edu.cn (K. He).

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Yellow River basins in China has shown a significant downward trend (Ma et al., 2010a). Significant downward trends in runoff between 1957 and 2000 were observed in the Haihe River basin, and human activities were found to account for > 60% of the reduction in runoff (Wang et al., 2013). Fenta et al. reported that the total reduction in mean annual streamflow caused by human activities was approximately 78% in the Agula watershed in northern Ethiopia (Fenta et al., 2017).

Quantifying the impacts of climate change and human activities on runoff changes is challenging; the impacts of climate change and human activities vary and require field investigations (Wang et al., 2013). Most studies analyze their effects through hydrological models, but such models require abundant data to support them, which are often obtained difficultly. Statistical and graphical methods have been used to effectively address runoff responses to various changes (Zhang et al., 2014a). In the present study, hydrological sensitivity analysis and an elasticity model are applied. Hydrological sensitivity analysis studies the effects of precipitation and potential evaporation on runoff to quantify the effects of climate change on runoff, allowing climate change effects to be distinguished from those of human activity (Liu et al., 2010; Zhang et al., 2008b; Zhao et al., 2010b). Climate elasticity models are also used to assess the impacts of climate change (Ma et al., 2010b; Zheng et al., 2009). However, it is very difficult to identify and distinguish the influences of various human activities due to nonlinear relations and other factors (Peng et al., 2013). Therefore, quantifying the impacts of climate change and human activities on hydrological processes is critical to the development of sustainable water resources management.

In calculating the impacts of climate change and human activities, most studies have focused on the whole region, few examples of subregion being studied. But in most cases, the study area is not a completely similar global one, and each sub-region has its own characteristics. Therefore, the study of the relationship between runoff change and climate change and human activities in the sub-region can provide a more detailed understanding of the situation of the regional water environment. For example, Yuan obtained different results for the areas east, south and west of Dongting Lake (Yuan et al., 2016). Conducting analyses at different scales from the whole to the part can help us to better describe the response relationships between runoff and both climate change and human activities in a study area, thus providing a method and a theoretical basis for the next step of water resource management.

The Beichuan River Basin is located in the northeast region of the Tibetan Plateau, which is known as “China's water tower”, as this area is the source of many rivers in China (Jiyuan and Shao, 2008). Recent studies have shown that the regional climate has become warm and humid (Gao et al., 2015; Piao et al., 2010). With the rapid development of the economy, the local water resource problem has become increasingly serious; however, a systematic quantification of climate change and the runoff impact of human activities in the Beichuan River Basin is lacking. Therefore, the present study aims to (1) analyze the changes in hydrological and meteorological data in the basin for a specific time period, (2) estimate the contributions of climate change and human activities to runoff variability, and (3) perform a comparative analysis of climate change and human activities in the region's sub-basins.

2. Materials and methods

2.1. Study area

The Beichuan River Basin (BCRB) lies between 100°51′E and 101°56′E and between 36°43′N and 37°23′N in the northeast region of the Tibetan Plateau. A tributary of the Yellow River, the basin consists of six small catchment areas (Fig. 1). Information on the six hydrographical and meteorological stations in the basin is provided in Table 1. Chaoyang station lies at the outlet of the river basin. The basin has an area of approximately 3371 km^2 and an elevation ranging from 2280 m to 4622 m. The river basin is located inland and has a weak continental climate with an annual average temperature of 2.8 °C. The annual mean precipitation is approximately 508 mm, and over 80% of the precipitation events occur between May and September (Fig. 2).

2.2. Data

Mean monthly meteorological data, including maximum, minimum and mean temperatures and humidity, and average monthly precipitation records from 1961 through 2013 were obtained from the Beichuan River Basin Administration Bureau. Potential evapotranspiration was calculated using the Penman mode (Wang and He, 2017). Calculation of mean precipitation in the basin was performed using the tessellation polygon method (Siu-Nganlam, 1983). Monthly average runoff data were obtained from Beichuan River Basin Administration Bureau, and water use data were obtained from Datong County Water Conservancy Bureau. The time period spanned from 1961 to 2013. In this study, the average runoff of the river basin was measured at Chaoyang station, which lies at the outlet of the watershed, and runoff data for each sub-basin were calculated by subtracting the values from upstream stations. Geospatial data were obtained by using a digital elevation model with a resolution of 30 m from the Data Sharing Infrastructure of Geospatial Data Cloud (http://www.gscloud.cn/), which was provided by the Chinese Academy of Sciences. The land use data set was provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). We used the land use data of 1990, 2000 and 2010, which were based on 1:100000 Landsat TM/ETM remote sensing images.

2.3. Methods

2.3.1. Trend test and change-point analysis method

The rank-based Mann-Kendall test was used to detect trends in this study. This test is commonly used to analyze trends in time-series data and has been widely used in hydrology (Kendall, 1955; Mann, 1945; Myronidis et al., 2012; Shadmani et al., 2012). Furthermore, this test can be used to detect and locate the approximate starting point of a trend in a runoff data series; if an intersection occurs within the confidence interval, it indicates a change point (Sneyers, 1977).

2.3.2. Double mass curve method

The double mass curve method (DMC) is a simple, convenient and widely used method in hydrological research (Gao et al., 2010). Briefly, the reference variable is set to X, the test variable is set to Y, and the observation period is N years. The calculation of variable X and variable Y enables the calculation of their annual cumulative values, which provides a new year-by-year cumulative sequence.

$$X_i' = \sum_{i=1}^{N} X_i \tag{1}$$

$$Y_i' = \sum_{i=1}^{N} Y_i \tag{2}$$

In the Cartesian coordinate system, based on the correlation between two variables, regression analysis is performed, and a graph of the relation between the two variables is constructed. The DMC can be used to assess the consistency of hydrological processes and derive runoff changes due to human activities (Zhang and Lu, 2009; Zhang et al., 2009). In this study, the DMC between precipitation and runoff was used to estimate the impact of human activities.

2.3.3. Framework for estimating the impact of climate change and human activity on runoff change

Despite the complexity of runoff processes, for a given catchment,

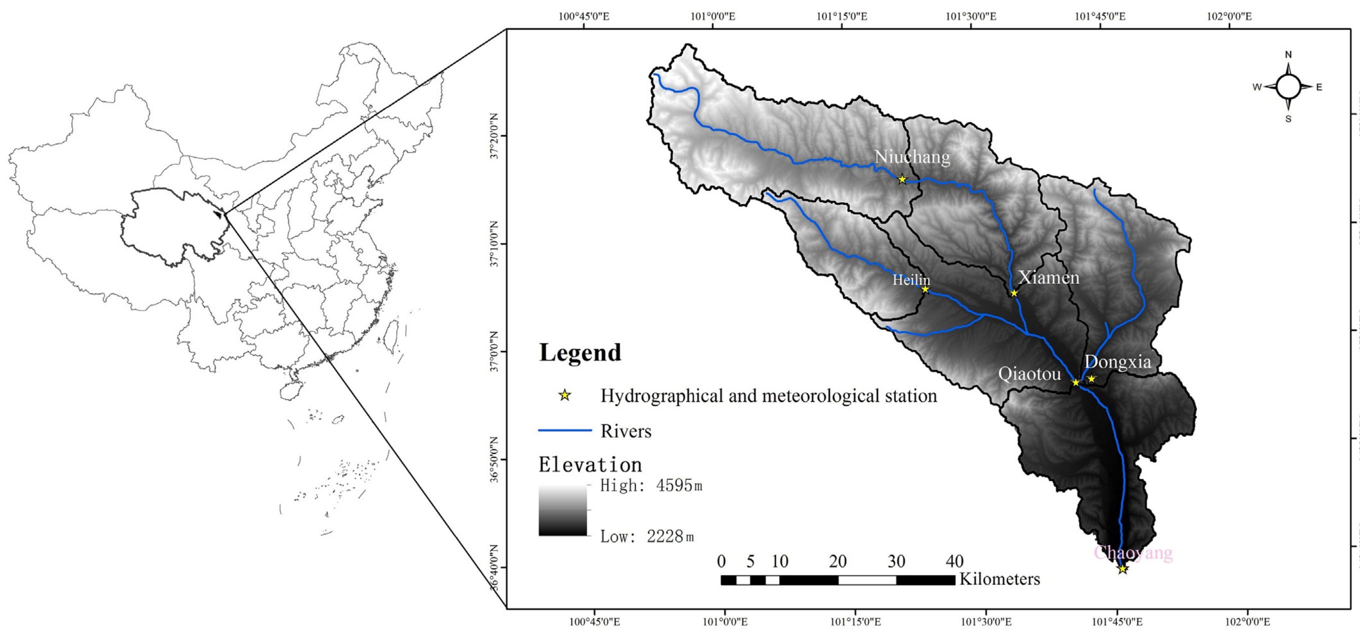

Fig. 1. Location of the Beichuan River Basin in China.

Table 1
The longitude, latitude, elevation and control area of the stations.

Station	Longitude (°E)	Latitude (°N)	Elevation (m)	Control area (km^2)
Niuchang	101.36	37.25	3236	784
Xiamen	101.57	37.07	2665	1308
Heilin	101.40	37.08	2840	281
Qiaotou	101.68	36.94	2508	2774
Dongxia	101.71	36.95	2558	547
Chaoyang	101.76	36.64	2324	3365

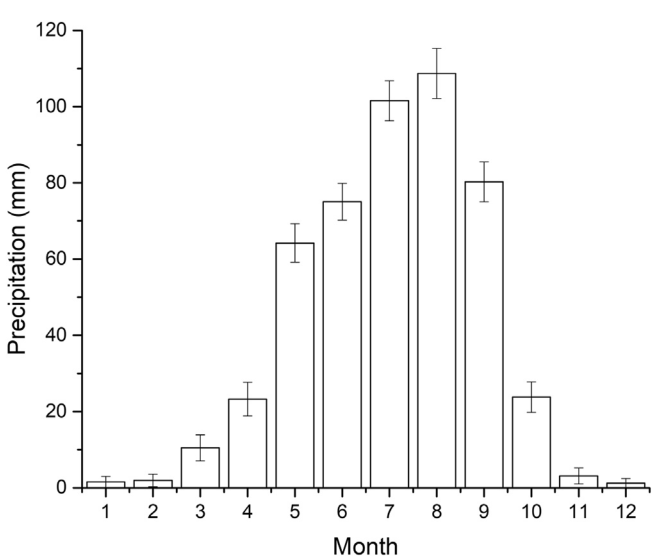

Fig. 2. Mean monthly precipitation in the Beichuan River Basin.

runoff can be modeled as a function of climate change and human activity (Zheng et al., 2009):

$$Q = f(C, H) \tag{3}$$

Here, Q is runoff, C represents the effects of climate factors on runoff processes, and H is a factor that represents the integrated effects of human activities on runoff. Furthermore, Eq. (3) can be transformed into (Zhang et al., 2008a)

$$\Delta Q = \Delta Q_C + \Delta Q_H \tag{4}$$

Here, ΔQ_C and ΔQ_H represent runoff changes due to climate change and human activities, respectively. Despite the interaction between climate change and human activities, climate change is mainly controlled by external conditions in a small basin; thus, on the basin scale, they are considered independent (Jiang et al., 2011).

2.3.4. Climate elasticity model

Climate elasticity is used to assess the sensitivity of runoff to climate change (Schaake and Waggoner, 1990). The elasticity of runoff to climate can be expressed as the proportional variation of runoff divided by the proportional change in climate change (such as precipitation), and the precipitation elasticity of runoff can be expressed by Eq. (5). Similar definitions were applied to potential evapotranspiration and the other climate variables.

$$\varepsilon_P(P, Q) = \frac{dQ/Q}{dP/P} = \frac{dQ}{dP}\frac{P}{Q} \tag{5}$$

Referring to previous studies (Fu et al., 2007; Sankarasubramanian et al., 2001; Zheng et al., 2009), this study considered both precipitation and mean temperature to establish climate elasticity. By establishing a binary linear regression equation of precipitation, mean temperature and runoff, the relationship between runoff and climate is described as

$$\Delta Q_i/\overline{Q} = \varepsilon_1 \cdot \Delta P_i/\overline{P} + \varepsilon_2 \cdot \Delta T_i/\overline{T} \tag{6}$$

Here, ε_1 and ε_2 are the elasticity of precipitation and annual mean temperature to runoff, respectively, and ΔT_i is the variation in the annual average temperature relative to the annual average temperature $\overline{T}$. The values of ε_1 and ε_2 were calculated according to Eq. (6) for precipitation, temperature and runoff for 1961–2013.

2.3.5. Hydrological sensitivity analysis method

The water balance in a basin over a long time scale (i.e., > 10 years) is

$$P = E + Q \tag{7}$$

Here, P is precipitation, E is the evapotranspiration in the basin, and Q is runoff.

According to Zhang et al. (2001) theory, evaporation and precipitation are related as follows:

$$\frac{E}{P}=\frac{1+\omega(E_P/P)}{1+\omega(E_P/P)+(E_P/P)^{-1}} \tag{8}$$

Here, Ep is potential evaporation; ω is the plant-available water coefficient, which is a comprehensive parameter related to the underlying surface of the vegetation and soil and reflects the availability of soil moisture to different types of vegetation. The recommended value of ω is 2.0 for woodland and 0.5 for grassland and arable land (McNulty et al., 2002). In this study, according to the annual precipitation, the potential evapotranspiration, and the runoff in the basin, the corresponding ω value can be determined by Eq. (8).

Based on Budyko theory (Budyko, 1974), both precipitation and potential evaporation (E_P) can change the water balance, and the change in the runoff can be expressed as follows (Ruud et al., 2004; Trask et al., 2017):

$$\Delta Q_C=\beta\Delta P+\gamma\Delta E_P \tag{9}$$

Here, β and γ are values of basin runoff sensitivity to precipitation and potential evapotranspiration, respectively. The sensitivity coefficients can be expressed as (Li et al., 2007)

$$\beta=\frac{1+2\phi+3\omega\phi^2}{(1+\phi+\omega\phi^2)^2} \tag{10}$$

$$\gamma=\frac{1+2\omega\phi}{(1+\phi+\omega\phi^2)^2} \tag{11}$$

Here, ϕ is the aridity index (equal to the potential evapotranspiration divided by the precipitation).

3. Results

3.1. Multi-year variation of hydro-meteorological factors

We addressed 53 years of data on temperature (T), precipitation (P), runoff (Q) and potential evaporation (E_P) as the meteorological characteristics in the basin and six sub-basins (Fig. 3 and Fig. 4).

Mann-Kendall trend tests are useful for analyzing the driving forces and behavior of runoff and climate variability over long time periods. The results of trend tests of 53 years of runoff (Q), precipitation (P), potential evaporation (E_P) and temperature (T) data are presented in Table 2. Precipitation, potential evapotranspiration and temperature of BCRB and six sub-basins showed increasing trends over time. Except for the runoff in the Xiamen and Heilin sub-basins, runoff in the basin showed a downward trend, unlike the trends of the meteorological factors. The decline rate of runoff ranged from -0.474 to $-0.991\ mm{\cdot}a^{-1}$, and that of the whole basin was $-0.698\ mm{\cdot}a^{-1}$.

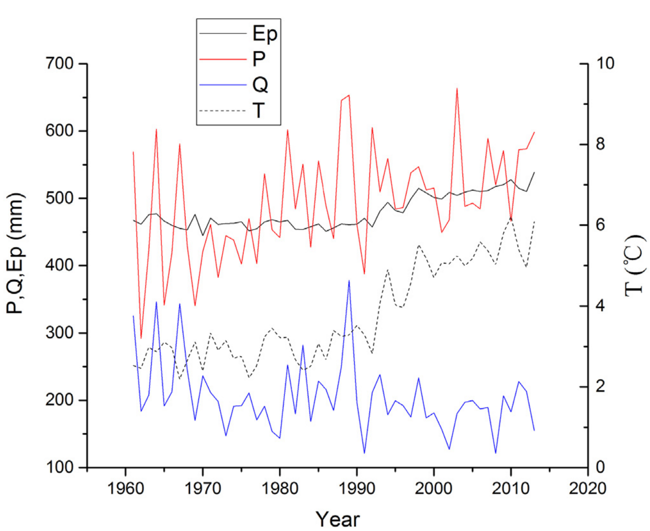

Fig. 3. Variation of meteorological factors in BCRB from 1961 to 2013.

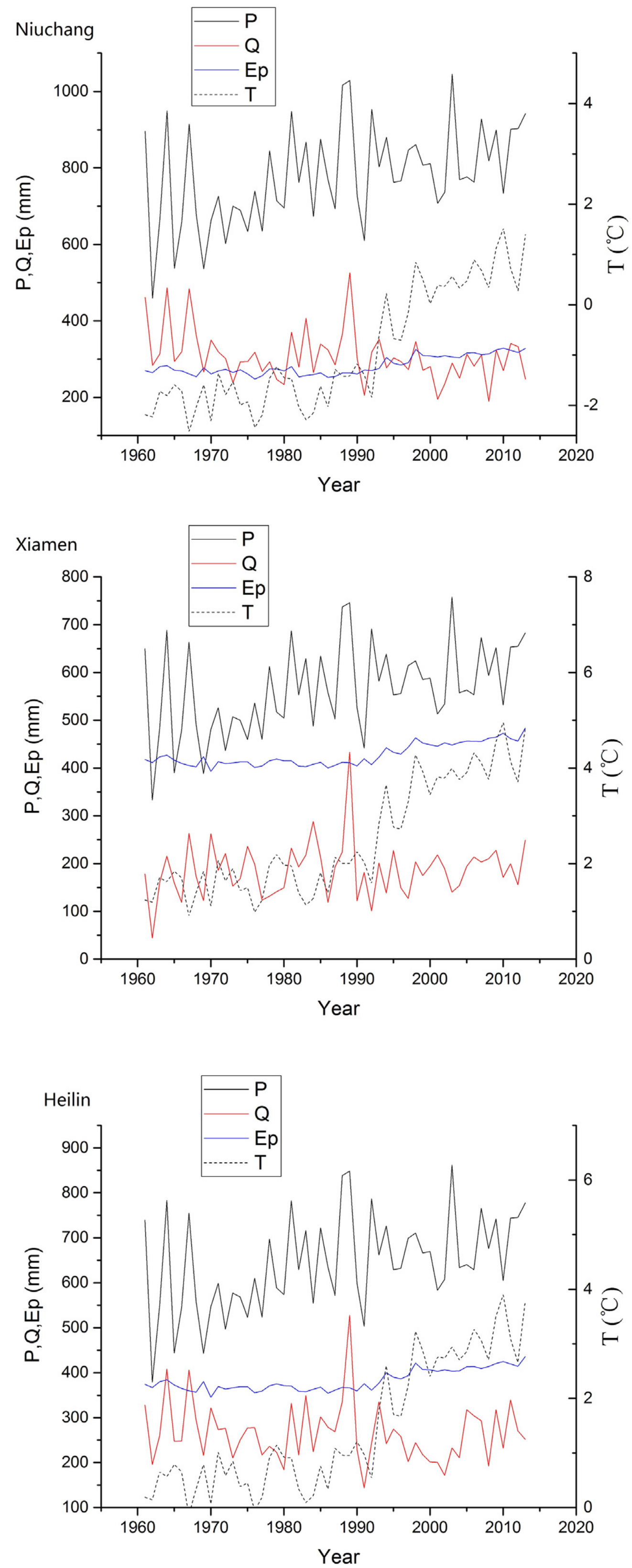

Fig. 4. Variation of meteorological factors in the six sub-basins from 1961 to 2013.

In addition, the Mann-Kendall change-point test was used to analyze the annual runoff. The results showed that the annual runoff of the

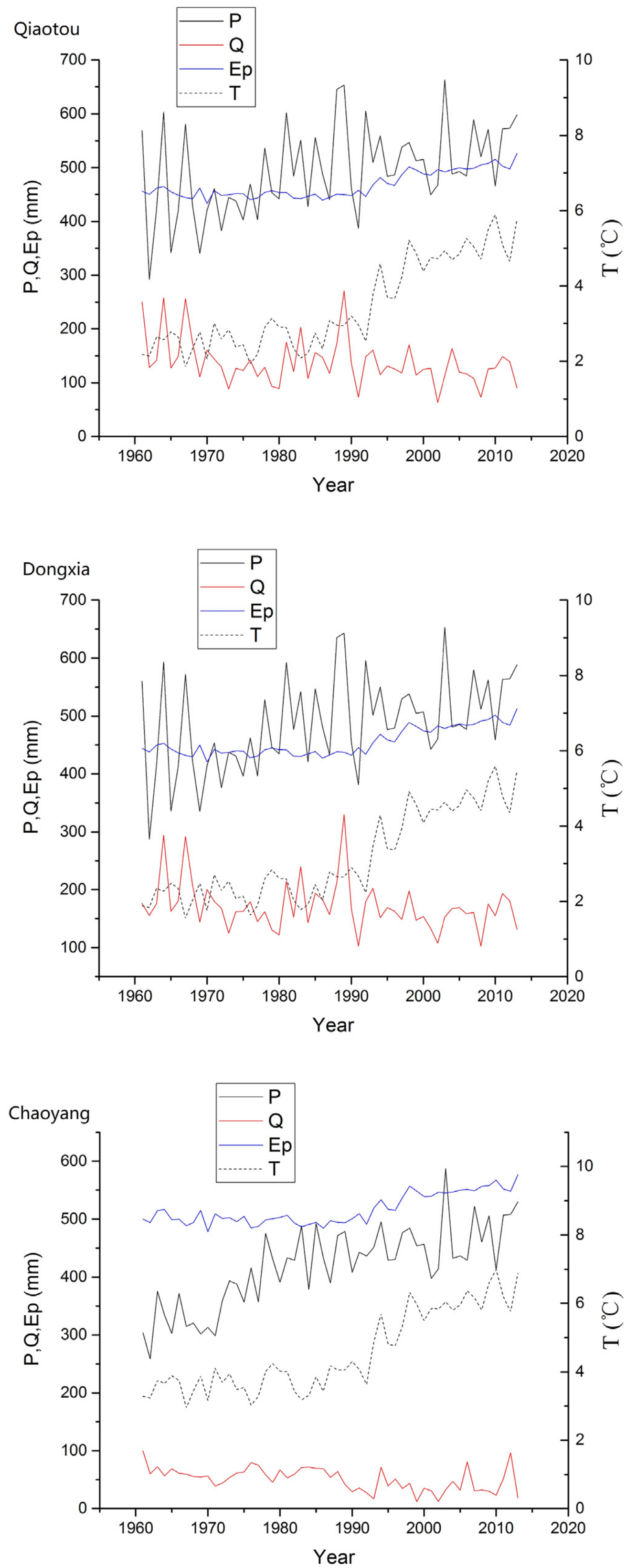

Fig. 4. (*continued*)

whole basin and the six sub-basins exhibited sudden changes within the period of study (Figs. 5(a) and 6). The UF line and UB line of the BCRB and the Niuchang, Heilin, Qiaotou, and Dongxia sub-basins intersected in 1972 and 1989, and the intersection points were within the critical values (Y = 1.96 and Y = −1.96) of the confidence interval for the significance level of 0.05. These results show that runoff mutation occurred in 1972 and 1989. The UF line and UB line of the Chaoyang sub-basin also intersected in 1972 and 1989, but the intersection point in 1972 fell below the critical value; therefore, the runoff was considered to have an abrupt point only in 1989. In contrast, the UF and UB lines of the Xiamen sub-basin intersected many times during the study period, and there were many abrupt points.

Further DMC analysis was used to verify the runoff mutation results (Fig. 5(b) and Fig. 7). The cumulative curve of precipitation and runoff can be divided into three straight lines in 1972 and 1989 with different slopes for the whole basin and four sub-basins. The precipitation and runoff curves of the Chaoyang sub-basin can be divided into two straight lines in 1989, and the slope changes greatly, showing that non-meteorological factors had a greater impact on runoff than did meteorological factors.

Therefore, the study period can be divided into a base period (1961–1971) and a change period (1972–2013), and the change period can be further divided into periods I (1972–1988) and II (1989–2013). The Chaoyang sub-basin is divided into two stages according to the abrupt point: the base period (1971–1988) and the change period (1989–2013). The division of regions at different times and meteorological and hydrological changes are shown in Table 3. The results show that in the relative base period, the runoff decreased by 10–40% during the change period, while the precipitation increased markedly during this period (7–20%). Potential evaporation slightly decreased during change period I, whereas that during change period II increased by 7–12%. The temperature showed an increase during change period I, and the increase of change period II was greater than that of change period I.

3.2. Effects of climate change on runoff variation

Table 3 shows the variations of runoff and meteorological factors during the base period and change period. It can be seen that the runoff of the Chaoyang sub-basin decreased rapidly during the change period, reaching a change of −38.78%, whereas the runoff of the Heilin sub-basin showed the smallest decrease among the sub-basins, changing by −9.80% (change period I) and − 11.22% (change period II). The runoff of the whole basin (BCRB) changed by −18.78% (change period I) and − 20.66% (change period II) during the change period. According to the hydrological sensitivity analysis of Eq. (9), the effect of climate change on runoff variation in each region was obtained. Similarly, the effects of climate change over different periods were derived based on Eq. (6) of the climate elasticity model (Table 4).

The difference in climate change is similar between the two methods, with the results validating each other. The table shows that the impacts of climate change on runoff in all regions are negative and that the effects in change period II are greater than those in change period I. In addition, the sensitivity coefficient of runoff to precipitation is greater than that to potential evaporation in all regions. Similarly, in the climate elasticity model, the elasticity coefficient of runoff to precipitation is larger than that to temperature.

Considering the results of the two methods together, the climate change in the watershed increased runoff during the change period. The Niuchang sub-basin showed the largest change in runoff, which reached approximately −55 mm (1972–1988) and −100 mm (1989–2013). The change in runoff caused by climate change was approximately −11 mm during the change period (1989–2013). The impact of climate change on runoff over the whole basin (BCRB) was different between the two change periods, with changes of approximately −24 mm (change period I) and −41 mm (change period II).

3.3. Effects of human activities on runoff variation

The effects of human activities on the water cycle in the watershed

Table 2
Trend analyses by Mann-Kendall tests.

	Q			*P*			E_P			*T*		
	Z	Trend	Slope	Z	Trend	Slope	Z	Trend	Slope	Z	Trend	Slope
			$mm{\cdot}a^{-1}$			$mm{\cdot}a^{-1}$			$mm{\cdot}a^{-1}$			$mm{\cdot}a^{-1}$
BCRB	−1.91	Downward	−0.698	3.74	Upward	2.763	5.59	Upward	1.291	6.54	Upward	0.066
Niuchang	−2.03	Downward	−0.991	4.11	Upward	4.351	5.33	Upward	1.240	6.77	Upward	0.056
Xiamen	1.13	No	−0.530	2.34	Upward	3.155	5.50	Upward	1.245	6.33	Upward	0.069
Heilin	−0.91	No	−0.511	3.15	Upward	3.590	5.47	Upward	1.224	6.56	Upward	0.070
Qiaotou	−2.31	Downward	−0.597	3.37	Upward	2.763	5.38	Upward	1.280	6.78	Upward	0.643
Dongxia	−1.68	Downward	−0.474	3.74	Upward	2.720	5.55	Upward	1.257	6.23	Upward	0.063
Chaoyang	−4.06	Downward	−0.732	4.05	Upward	3.579	5.58	Upward	1.359	6.07	Upward	0.066

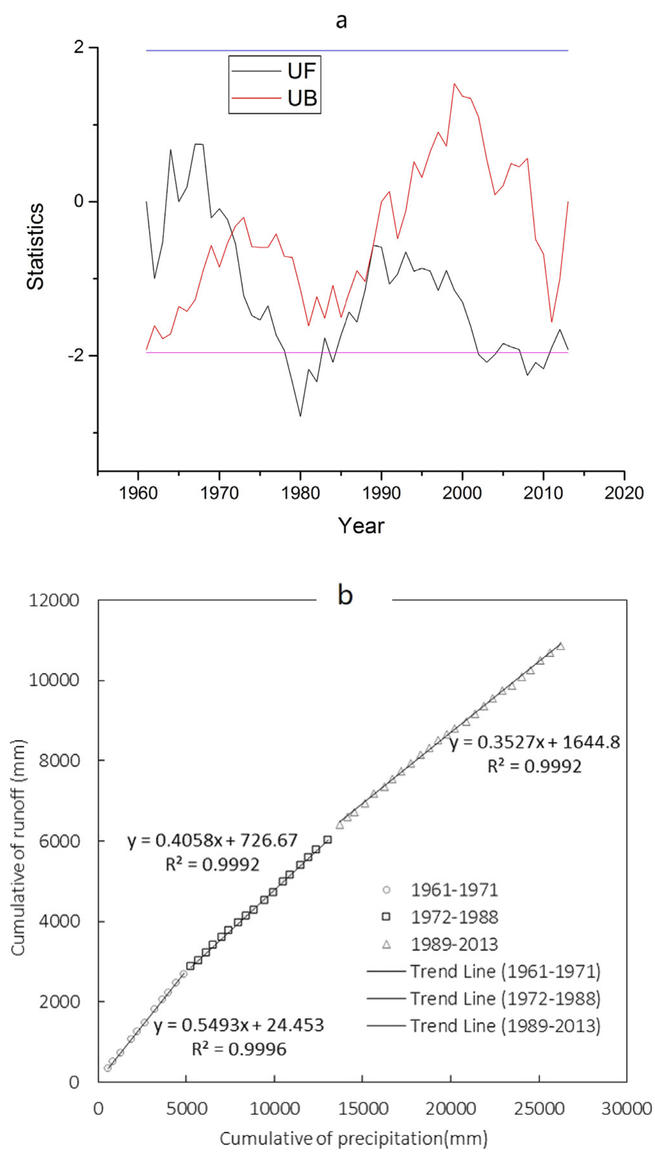

Fig. 5. (a) Mann-Kendall change-point detection for the 1961–2013 time series in the BCRB;
(b) Double cumulative curve of annual precipitation and runoff in the BCRB.

are mainly reflected in two aspects: direct and indirect. Direct impacts include direct artificial water intake (or irrigation) and cross-regional water transfer, for example, the South-to-North Water transfer Project in China has changed the regional water cycle by transferring water from the south to the north. Indirect impacts alter regional water cycles by altering underlying watershed surfaces such as land use change and new water facilities (Zhang et al., 2013).

Based on the data of water supply in the Beichuan River Basin from 1961 to 2013, we obtained a multiyear variation curve of water supply (Fig. 8). During the period of study, the water supply in the Beichuan River Basin increased by a large margin and increased more rapidly after 1989. Table 5 shows that during the change period (1972–2013), the water supply increased by 49.76% (change period I) and 213.85% (change period II).

The land use in the study area is divided into six types: barren land, construction land, cropland, forest, grassland and water. The land use classification for the whole basin and six sub-basins is shown in Fig. 9, and the land use areas for these regions are shown in Table 6.

The main types of land use in BCRB are cropland, forest and grassland, which together account for approximately 90% of the total area. The grassland area was the largest, accounting for approximately 47% of the total area. However, land use varied among the six sub-basins. Cropland area in the Niuchang sub-basin accounted for the lowest proportion among the land use types, approximately 0.4%, whereas the proportion of grassland area in this sub-basin was the largest, reaching 56%. The forest area in the Xiamen sub-basin was the largest among the six sub-basins. The Chaoyang sub-basin had the lowest amount of forest area, representing only approximately 6%. The proportions of construction land were highest for the Chaoyang and Qiaotou sub-basins, whereas those of the Xiamen and Heilin sub-basins were the lowest. Due to the accuracy of the data, the water and construction land in the Niuchang sub-basin, the water in the Xiamen sub-basin in 1990 and 2000, and the water in the Heilin and Dongxia sub-basins were not calculated.

Fig. 10 shows the land use change in BCRB and the six sub-basins during two stages. In BCRB, grassland and construction land areas increased in both periods, and the increases were more rapid in 2000–2010, with total increases of 707 and 924 hm^2, respectively. The area of cropland decreased in both periods and was reduced by 1309 hm^2 in 2000–2010. The areas of forest and construction land in the Niuchang sub-basin changed markedly; the forest area changed by −98 hm^2 and 95 hm^2 in the two periods, and the construction land area increased by 7 hm^2 and 105 hm^2. In the Xiamen sub-basin, the cropland area decreased in 2000–2010 (−244 hm^2), the forest and grassland area increased (by 122 hm^2 and 87 hm^2, respectively), and the water body increased significantly (335 hm^2); according to records, a reservoir was built there in 2001. In the Heilin sub-basin, the forest area increased by 103 hm^2 and 93 hm^2 in the two periods, and the grassland area changed by −78 hm^2 and 14 hm^2. In the Qiaotou sub-basin, in the two periods, the cropland area decreased by 55 hm^2 and 163 hm^2, the forest area changed by −141 hm^2 and 184 hm^2, the grassland area increased by 115 and 207 hm^2, and the construction land increased by 68 and 190 hm^2. In the Dongxia sub-basin, the forest area increased by 24 and 100 hm^2, and the grassland changed by 174 hm^2 and −3 hm^2. In the Chaoyang sub-basin, the area of cropland decreased significantly (−282 hm^2 and −899 hm^2), the area of forest changed by −118 hm^2

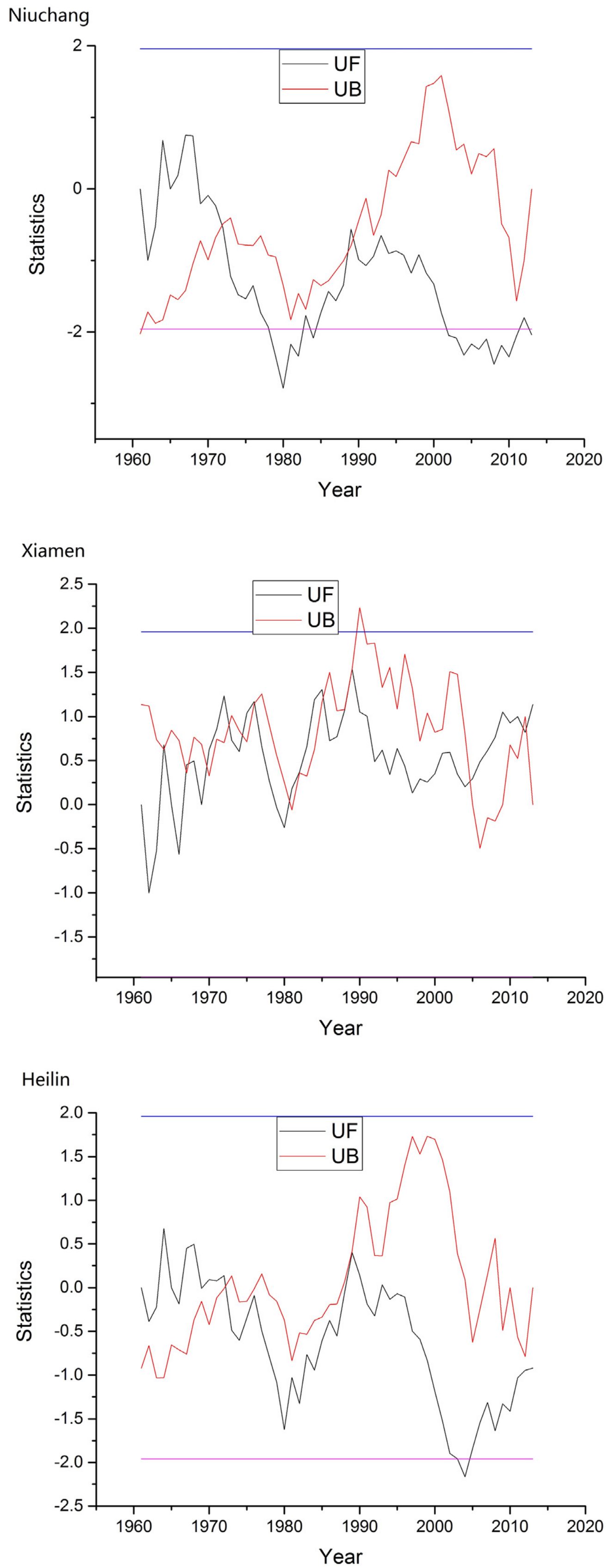

Fig. 6. Mann-Kendall change-point detection for the six sub-basins.

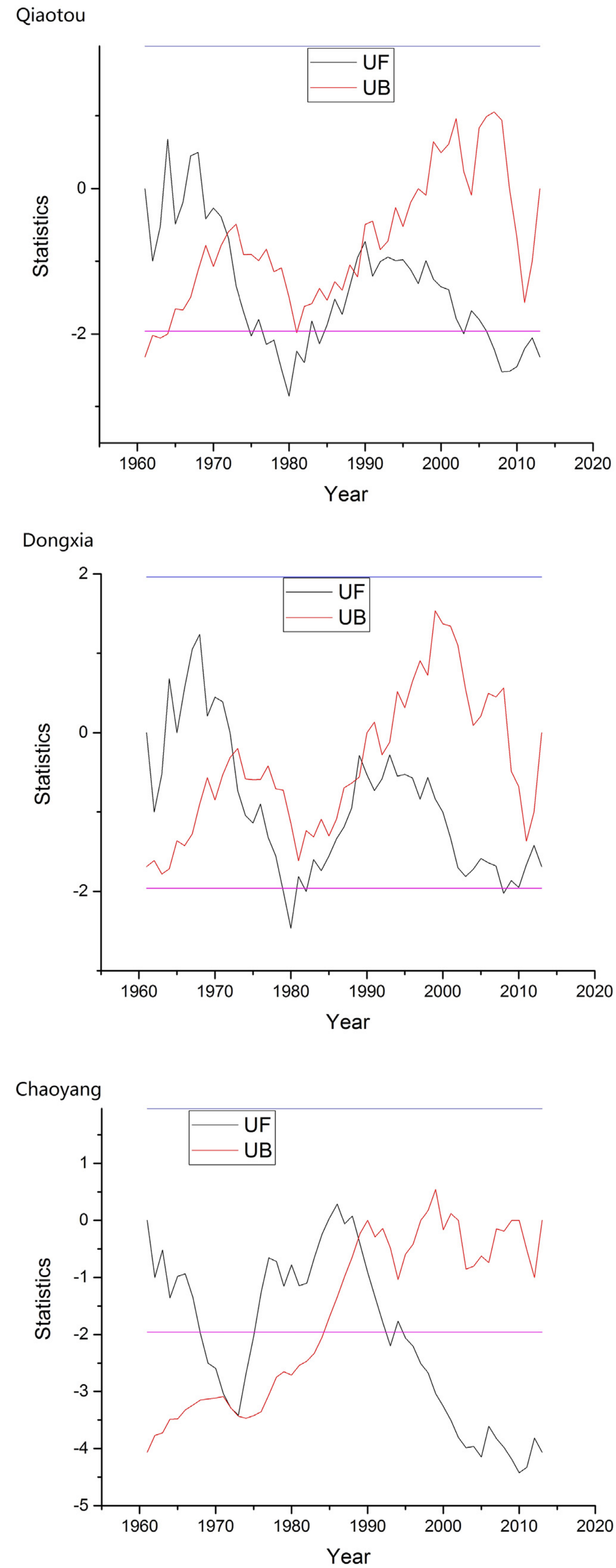

Fig. 6. (*continued*)

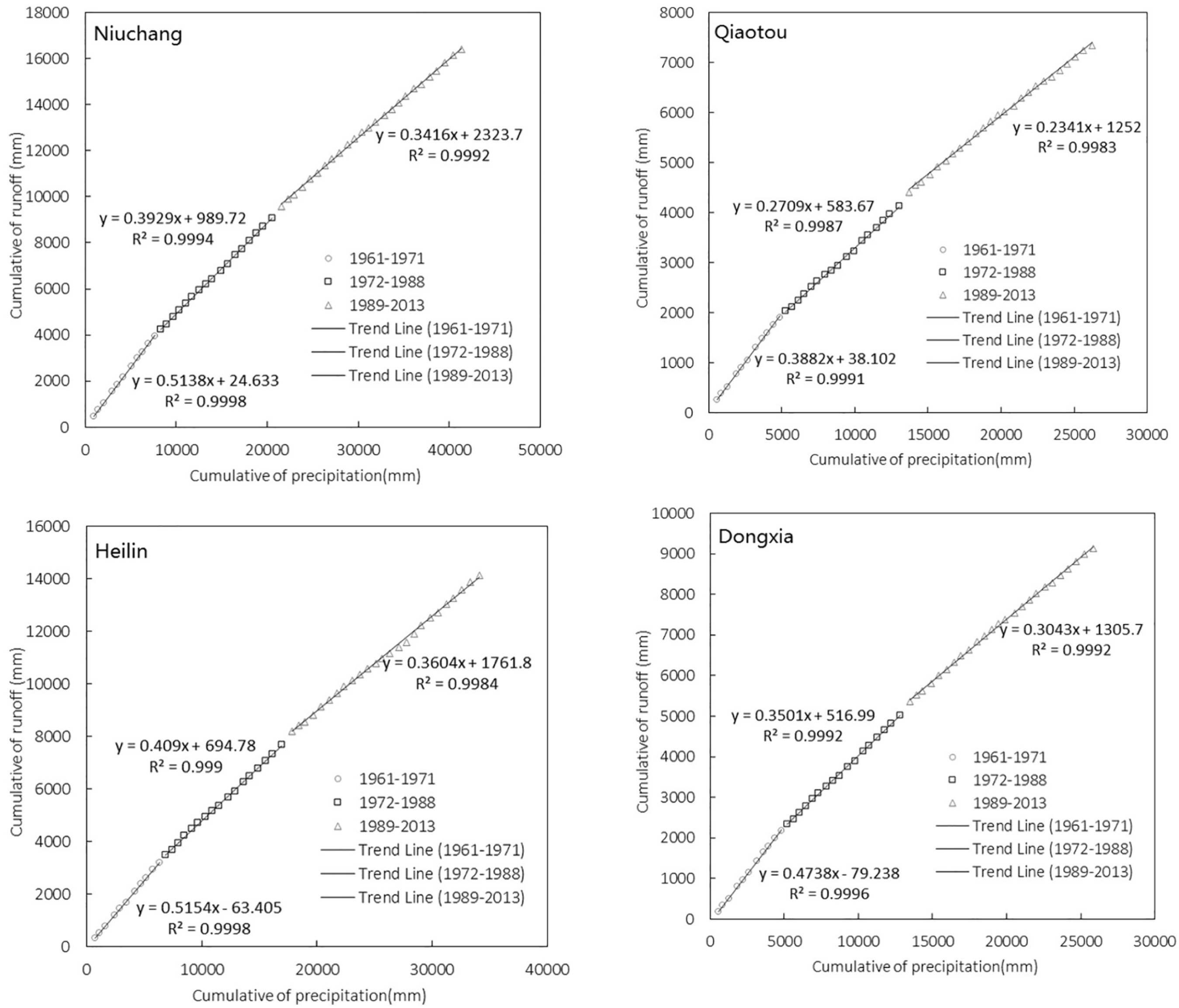

Fig. 7. Double cumulative curve of annual precipitation and runoff in five sub-basins.

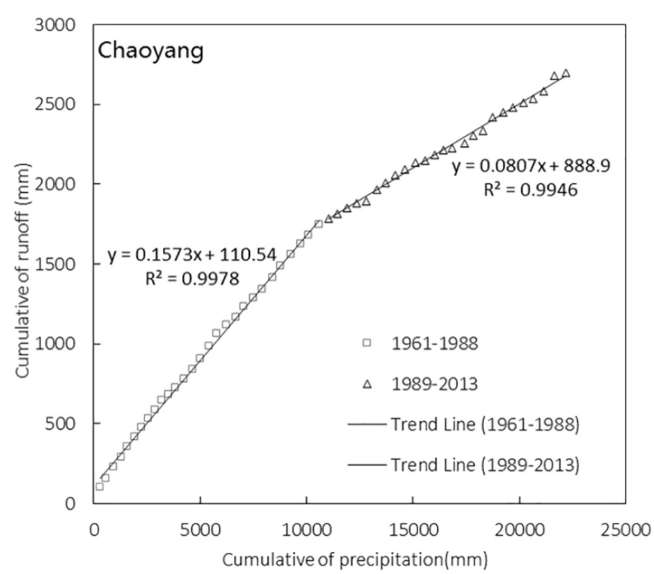

Fig. 7. (*continued*)

and 368 hm^2, the area of grassland changed by -19 hm^2 and 297 hm^2, and the area of construction land increased markedly (398 hm^2 and 635 hm^2).

3.4. Impacts of climate change and human activities on runoff change

According to Eq. (4), runoff changes can be attributed to climate change and the impacts of human activities. Based on the calculated effects of climate change, we derived the effects of human activities on runoff changes. The results of the hydrological sensitivity analysis and climate elasticity model are shown in Table 7.

It can be seen that the results obtained from the two methods, i.e., the hydrological sensitivity analysis and the climate elasticity model, are approximately the same. In the BCRB and the five sub-basins of Niuchang, Qiaotou, Heilin, Dongxia and Chaoyang, human activities had dominant effects in runoff reduction, and the contribution of climate change was only 24–37%. The contribution of human activities to the runoff variation of BCRB during the change period (1972–2013) was 74.02% and 68.62% (hydrological sensitivity analysis) and 74.62% and 69.11% (climate elasticity model) for change periods I and II, respectively. The contribution of human activities in the Qiaotou,

Table 3
Meteorological and hydrological changes during the base period and the change period.

	Period	*Q* (mm)	Change	*P* (mm)	Change	E_P (mm)	Change	*T* (°C)	Change
Niuchang	1961–1971	357.98		698.77		269.34		−1.91	
	1972–1988	301.33	−15.83%	756.41	7.45%	263.65	−2.11%	−1.78	6.81%
	1989–2013	293.10	−18.13%	831.22	18.95%	302.41	12.28%	0.11	105.67%
Qiaotou	1961–1971	172.76		443.72		452.23		2.45	
	1972–1988	131.33	−23.98%	480.32	8.26%	448.21	−0.89%	2.58	5.31%
	1989–2013	128.17	−25.81%	527.82	20.29%	487.39	7.77%	4.48	82.42%
Heilin	1961–1971	290.84		576.48		368.81		0.46	
	1972–1988	262.35	−9.80%	624.03	6.85%	364.84	−1.08%	0.59	28.21%
	1989–2013	258.22	−11.22%	685.76	16.38%	401.09	8.75%	2.48	437.84%
Dongxia	1961–1971	197.28		436.73		439.77		2.15	
	1972–1988	167.82	−14.93%	472.75	7.74%	436.00	−0.86%	2.28	6.05%
	1989–2013	164.11	−16.81%	519.51	19.74%	473.93	7.77%	4.18	93.90%
Chaoyang	1961–1988	62.32		377.74		497.74		3.64	
	1989–2013	38.15	−38.78%	463.56	22.72%	537.90	8.07%	5.58	53.44%
BCRB	1961–1971	243.05		443.72		464.18		2.78	
	1972–1988	197.65	−18.68%	480.32	7.43%	459.84	−0.94%	2.90	4.34%
	1989–2013	192.85	−20.66%	527.82	19.35%	499.82	7.68%	4.79	72.17%

Dongxia and Chaoyang sub-basins was higher than that in the other two sub-basins; the contributions in the former three regions according to the hydrological sensitivity analysis were 73.70% (1972–1988) and 67.73% (1989–2013), 70.01% (1972–1988) and 65.35% (1989–2013), and 75.18% (1989–2013), respectively. Furthermore, in all of the sub-basins except the Chaoyang sub-basin, the contribution of climate change was higher in change period II than in change period II.

4. Discussion

Runoff in Beichuan River Basin showed a decreasing trend during the study period; however, the analyses showed that annual precipitation was increased. The DMC also showed that the runoff decreased markedly during the change period. These findings indicate that changes in factors other than precipitation led to the decrease in runoff. Climate change and human activity are generally considered to be two major factors contributing to runoff change (Lin et al., 2007; Piao et al., 2007). In this study, we found that climate change in the study area increased runoff, whereas human activities reduced runoff. Both the Mann-Kendall change-point tests and the DMC analysis showed that 1972 and 1989 were the abrupt points of runoff change. The time period between these years corresponds to land reform movement in China, in which land was distributed to farmers (Yang and Fei, 2009a). In our assessment of runoff decline, we concluded that human activity

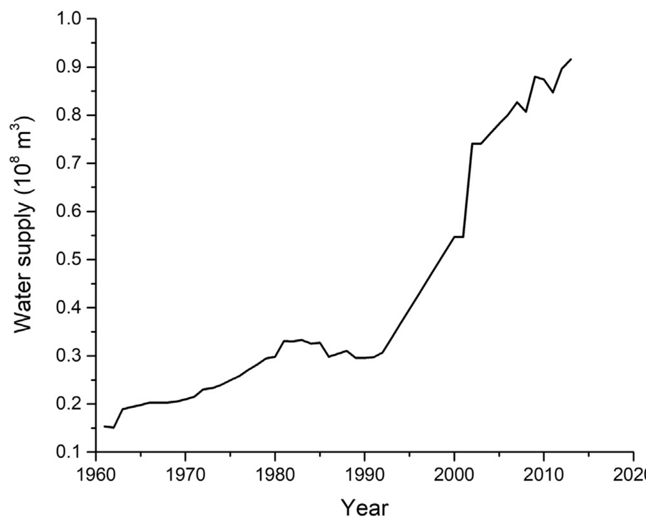

Fig. 8. Variation curve of the water supply in Beichuan River Basin (1961–2013).

Table 4
Estimation of climate change by hydrological sensitivity analysis and the climate elasticity model.

	Period	*Q* (mm)	Hydrological sensitivity analysis			Climate elasticity		
			ΔQ_C (mm)	β	γ	ΔQ_C (mm)	ε_P	ε_T
BCRB	1961–1971	243.05					1.004	−0.554
	1972–1988	197.65	−24.55	0.633	−0.320	−23.41		
	1989–2013	192.85	−42.31	0.643	−0.331	−40.57		
Niuchang	1961–1971	357.98					0.851	0.318
	1972–1988	301.33	−59.10	0.947	−0.797	−54.76		
	1989–2013	293.10	−98.96	0.945	−0.793	−100.82		
Qiaotou	1961–1971	172.76					1.187	−0.600
	1972–1988	131.33	−23.74	0.613	−0.327	−24.97		
	1989–2013	128.17	−40.56	0.624	−0.338	−38.23		
Heilin	1961–1971	290.84					0.898	−0.095
	1972–1988	262.35	−40.82	0.809	−0.595	−37.41		
	1989–2013	258.22	−69.48	0.814	−0.604	−65.21		
Dongxia	1961–1971	197.28					0.813	−0.310
	1972–1988	167.82	−22.07	0.579	−0.322	−22.10		
	1989–2013	164.11	−37.45	0.590	−0.334	−34.87		
Chaoyang	1961–1988	62.32					0.245	−1.021
	1989–2013	38.15	−11.91	0.340	−0.430	−10.48		

Table 5
Changes in the water supply in Beichuan River Basin during the base and change periods.

Period	Water supply (10^8 m^3)	Change
1961–1971	0.1931	
1972–1988	0.2892	49.76%
1989–2013	0.6061	213.85%

was the leading factor contributing to runoff decline, consistent with most previous studies (Fenta et al., 2017; Jiang et al., 2017; Wang et al., 2010). The multi-year water supply curve shown in Fig. 8 and the changes in land use type shown in Fig. 9 also reflect the rapid growth of human activity during the study period. The contribution of climate change to runoff change increased during change period II, and the corresponding contribution of human activities decreased, which is related to the increase in precipitation caused by global warming (JianQi, 2013; Xue et al., 2017). The increase in temperature over many years reported in this paper confirms this trend.

We divide the whole basin into six sub-basins according to the catchment areas were controlled by six hydro-meteorological stations in the Beichuan River Basin. Compared with the whole basin, the individual sub-basins exhibited different patterns. Runoff in BCRB showed a downward trend in 1961–2013, but no significant change trends were observed for the Xiamen and Heilin sub-basins, whereas runoff in the Xiamen sub-basin changed sharply during the study period. The extent of runoff decrease also differed among the sub-basins, with the Chaoyang sub-basin showing the greatest decrease during the change period (1989–2013), reaching 38.78%. This value is much higher than the decreases of 18.68% (change period I) and 20.66% (change period II) observed for the whole basin. In contrast, the Heilin sub-basin showed the smallest decrease, decreasing by only 9.5% (change period I) and 11.22% (change period II) during the change period (1972–2013). In addition, precipitation showed an increasing trend in each sub-basin, with the largest change observed in the Chaoyang sub-basin. This sub-based also showed the greatest temperature increase, with the temperature increasing by half. However, in general, the precipitation growth trend in the change period was largely consistent among the sub-basins, indicating that precipitation was largely free from external interference (Yuan et al., 2016).

In estimating the impacts of human activities on runoff change, it was found that the contributions of both the Chaoyang and Qiaotou sub-basins to human activities were greater than those of the remaining sub-basins. The impact of human activities in the Niuchang sub-basin was slightly higher than that in the Heilin sub-basin, with the human activities in the two sub-basins being less intense than those in the other areas. The land use types changed greatly in 1990–2010. The area of cropland decreased in Beichuan River Basin, and the areas of forest, grassland and construction land increased greatly from 2000 to 2010. The increases in forest and grassland area are related to the return of cropland to forest and grassland, which began at the end of the 20th century (Wang and Ying, 2010). China's economy developed rapidly during this period, including in the study area, and the increase in construction land reflects this economic growth (Zhang et al., 2014b). However, the change in land use types differed among the sub-basins. Although the areas of forest and grassland increased markedly in all six sub-basins, cropland area decreased greatly only in the Xiamen, Qiaotou and Chaoyang sub-basins, indicating the effective return of cropland to forest and grassland in these areas. In 2000, a new reservoir was built in the Xiamen sub-basin, and the area of water changed markedly. The human activities and climate change jointly lead to severe fluctuations in the runoff of the Xiamen sub-basin during the study period. The area of construction land increased markedly in the Chaoyang and Qiaotou sub-basins. These two regions are the most densely populated areas of the Beichuan River Basin, and the impact of

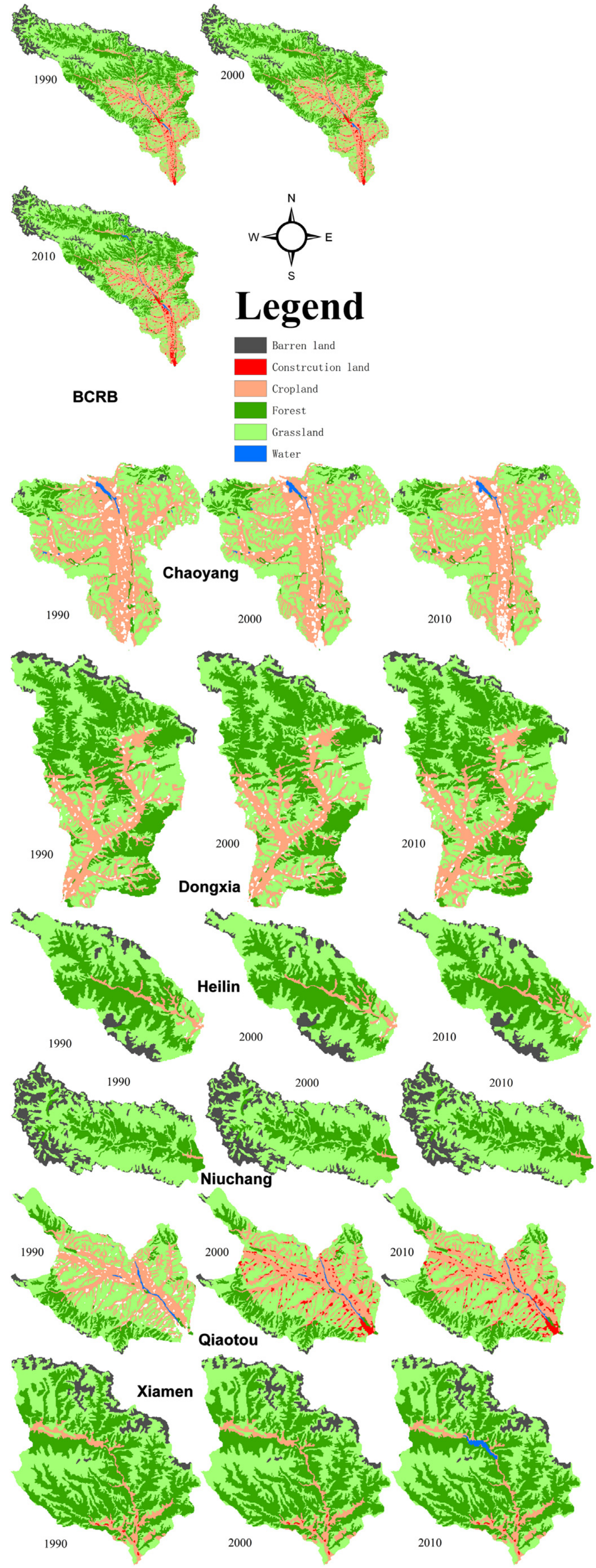

Fig. 9. Spatial maps of land use in 1990, 2000 and 2010.

Table 6
Land use area in 1990, 2000, and 2010.

(hm^2)		Cropland	Forest	Grassland	Water	Construction land	Barren land
1990	BCRB	58,070	84,788	160,892	784	7210	25,562
	Niuchang	360	17,776	44,593			16,387
	Xiamen	3341	22,216	22,135		85	3369
	Heilin	1341	11,439	14,286		89	2742
	Qiaotou	17,828	9321	31,269	419	2567	663
	Dongxia	9842	20,359	21,550		1072	1757
	Chaoyang	25,358	3677	27,059	365	3397	644
2000	BCRB	57,861	84,683	161,317	721	7712	25,012
	Niuchang	352	17,678	44,600			16,486
	Xiamen	3433	22,341	22,361		95	2916
	Heilin	1330	11,542	14,208		80	2737
	Qiaotou	17,773	9180	31,384	324	2635	771
	Dongxia	9897	20,383	21,724		1107	1469
	Chaoyang	25,076	3559	27,040	397	3795	633
2010	BCRB	56,552	85,645	162,024	1037	8636	23,412
	Niuchang	352	17,773	44,705			16,286
	Xiamen	3189	22,463	22,448	335	172	2539
	Heilin	1323	11,635	14,222		95	2622
	Qiaotou	17,610	9364	31,591	306	2825	371
	Dongxia	9901	20,483	21,721		1114	1361
	Chaoyang	24,177	3927	27,337	396	4430	233

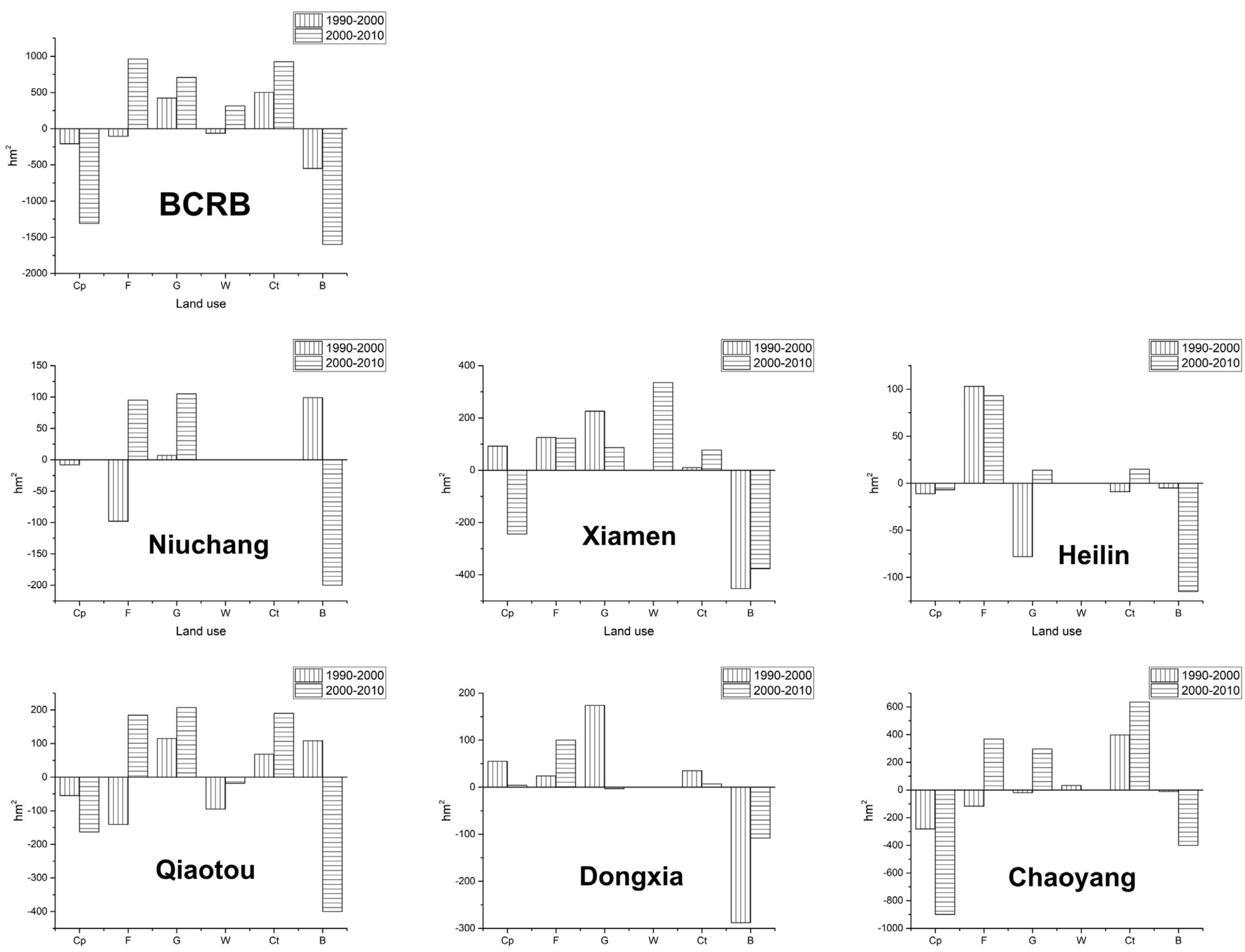

Fig. 10. Land use area changes in 1990–2000 and 2000–2010. In the figure, the abbreviations Cp, F, G, W, Ct and B denote cropland, forest, grassland, water, construction land and barren land, respectively.

Table 7
The contributions of climate change and human activities to runoff change in Beichuan River Basin and its sub-basins during 1961–2013.

	Period	Hydrological sensitivity analysis				Climate elasticity			
		Climate change		Human activities		Climate change		Human activities	
		Amount (mm)	Percentage	Amount (mm)	Percentage	Amount (mm)	Percentage	Amount (mm)	Percentage
BCRB	1961–1971								
	1972–1988	−24.55	25.98%	69.95	74.02%	−23.41	25.38%	68.81	74.62%
	1989–2013	−42.31	31.38%	92.52	68.62%	−40.57	30.89%	90.77	69.11%
Niuchang	1961–1971								
	1972–1988	−59.10	33.80%	115.76	66.20%	−54.76	32.95%	111.42	67.05%
	1989–2013	−98.96	37.65%	163.84	62.35%	−100.82	37.83%	165.71	62.17%
Qiaotou	1961–1971								
	1972–1988	−23.74	27.70%	65.17	73.30%	−24.97	27.33%	66.39	72.67%
	1989–2013	−40.56	32.27%	85.15	67.73%	−38.23	31.58%	82.82	68.42%
Heilin	1961–1971								
	1972–1988	−40.82	37.06%	69.31	62.94%	−37.41	36.21%	65.90	63.79%
	1989–2013	−69.48	40.49%	102.11	59.51%	−65.21	40.00%	97.83	60.00%
Dongxia	1961–1971								
	1972–1988	−22.07	29.99%	51.53	70.01%	−22.10	30.01%	51.56	69.99%
	1989–2013	−37.45	34.65%	70.62	65.35%	−34.87	33.88%	68.04	66.12%
Chaoyang	1961–1988								
	1989–2013	−11.91	24.82%	36.08	75.18%	−10.48	23.22%	34.65	76.78%

human activities on runoff is great.

There are some uncertainties in this study. First, in estimating the contributions of climate change and human activities to runoff changes using a climate elasticity model and hydrological sensitivity analysis, the results of the two methods were similar but nonetheless different. In this study, we used a climate elasticity model of multi-year precipitation and annual mean temperature to estimate the contribution of climate change, but other climate factors also impact climate change. In addition, the hydrological sensitivity analysis method is only suitable for analyzing the variation of runoff based on annual average precipitation, but seasonal or extreme precipitation will also affect the runoff process (Zhao et al., 2010a). Second, in framing the impacts of climate change and human activities on runoff variability, it was assumed that climate change and human activity are independent of each other (Zheng et al., 2009), but they are linked; for instance, deforestation adds to carbon in the atmosphere, which increases temperatures and causes climate change (Wang et al., 2010). Therefore, future research should improve the accuracy of estimation considering these uncertainties.

5. Conclusion

To estimate the impacts of climate change and human activities on runoff change in the Beichuan River Basin, hydrological and meteorological data for 1961–2013 were analyzed in this paper. The study period was divided into two stages: a base period (1961–1971) and the change period (1972–2013). The change period was further divided into two periods: change period I (1972–1988) and change period II (1989–2013). A climate elasticity model and hydrological sensitivity analysis were used to estimate the contributions of climate change and human activities during the change period.

The results showed that human activity was the dominant factor in runoff decline in Beichuan River Basin, with contributions of approximately 74% (change period I) and 69% (change period II). The contribution of climate change increased during change period II, with contributions of approximately 26% (change period I) and 31% (change period II). The water supply in the basin increased rapidly during the period of change, with an increase of 213.85% in 1989–2013 relative to the base period value. Furthermore, great progress in the conversion of cropland to forest and grassland was observed, and the area of construction land increased rapidly.

Unlike the periods determined for the whole basin, the base period and change period in the Chaoyang sub-basin were 1961–1988 and 1989–2013, respectively. Human activities played a leading role in runoff decline in all sub-basins. The Chaoyang sub-basin exhibited the most pronounced runoff decline among the sub-basins, and the contribution of human activities was also the highest for this sub-basin. The return of cropland to forest and grassland was most apparent in the Chaoyang and Qiaotou sub-basins, and the significant increase in construction land in these two sub-basins reflects the large change in human activities.

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